

## EXOPLANET HD 209458b (OSIRIS\*): EVAPORATION STRENGTHENED

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## ABSTRACT

Following re-analysis of *Hubble Space Telescope* observations of primary transits of the extrasolar planet HD 209458b at Lyman  $\alpha$ , Ben-Jaffel (2007, BJ007) claims that no sign of evaporation is observed. Here we show that, in fact, this new analysis is consistent with the one of Vidal-Madjar et al. (2003, VM003) and supports the detection of evaporation. The apparent disagreement is mainly due to the disparate wavelength ranges that are used to derive the transit absorption depth. VM003 derives a  $(15 \pm 4)\%$  absorption depth during transit over the core of the stellar Lyman  $\alpha$  line (from  $-130$  km/s to  $+100$  km/s), and this result agrees with the  $(8.9 \pm 2.1)\%$  absorption depth reported by BJ007 from a slightly expanded dataset but over a larger wavelength range ( $\pm 200$  km/s). These measurements agree also with the  $(5 \pm 2)\%$  absorption reported by Vidal-Madjar et al. (2004) over the whole Lyman  $\alpha$  line from independent, lower-resolution data. We show that stellar Lyman  $\alpha$  variability is unlikely to significantly affect those detections. The H I atoms must necessarily have velocities above the escape velocities and/or be outside the Roche lobe, given the lobe shape and orientation. Absorption by H I in HD 209458b's atmosphere has thus been detected with different datasets, and now with independent analyses. All these results strengthen the concept of evaporating hot-Jupiters, as well as the modelization of this phenomenon.

*Subject headings:* planetary systems — stars: individual (HD 209458) — spectroscopy

## 1. INTRODUCTION

Few detections of extrasolar planets' atmospheric species are reported so far, but they have been recognized as important steps in our understanding of these objects. Of particular interest are the direct detections with the *Hubble Space Telescope* (HST) during primary transits of Na I by Charbonneau et al. (2002) as well as HI, OI and CII by Vidal-Madjar et al. (2003, 2004) (hereafter VM003 and VM004) and Ballester et al. (2007).

The recent paper by Ben Jaffel (2007) (hereafter BJ007) however casts some doubt on many aspects of the HI detection in the upper atmosphere of HD 209458b and on the implication that the planet is evaporating due to the large energy input from its nearby host star (e.g., Lecavelier des Etangs 2007). Consequently, a related large number of theoretical studies would have to be revised.

In the present rebuttal paper, we discuss the BJ007 arguments and show where they are misleading.

## 2. WHERE IS THE DIFFERENCE ?

BJ007 completed a new data analysis based on sampling the same observations as VM003 in a different temporal manner, and adding data from two HST orbits from an archival program completed at another epoch (two orbits added to the nine HST orbits of the VM003 observations). From the resulting new Lyman  $\alpha$  transit light curve, the transit absorption depth is evaluated by integrating the Lyman  $\alpha$  flux in two ranges : “blue” (1214.83-1215.36Å) and “red” (1215.89-1216.43Å). This

slightly increases the wavelength domain excluded from the analysis because of geocoronal contamination, from 1215.5-1215.8Å in VM003 to 1215.36-1215.89Å in BJ007. This has, however, no significant consequences on the evaluation as shown in the Figure 4 of VM003.

BJ007 evaluates the transit depth by fitting a light curve over the observations sampled by 300s sub-exposures as a function of the planet orbital phase. The resampled observations show some level of variability mainly due to the variation of the stellar Lyman  $\alpha$  flux. The fitting procedure “smooths” these variations as if all observations were made with an average stellar Lyman  $\alpha$  flux. This gives an average HI absorption during the transit of  $(8.9 \pm 2.1)\%$  by considering a wavelength range from 1214.83 to 1216.43 Å which corresponds to  $\sim \pm 200$  km/s in velocity space.

The data analysis of BJ007 is not put into question here. The major differences between BJ007 and VM003 are on the data interpretation. Both analyses provide a Lyman  $\alpha$  line flux as a function of time and wavelength, which includes possible stellar variations and planetary transit signature. The differences lie i) in the wavelength ranges used to convert the spectra, as a function of time, into a single absorption depth measurement and ii) in the reference flux used to correct for the intrinsic stellar flux variations.

The Lyman  $\alpha$  emission of the star can significantly vary from epoch to epoch. Because there is no detectable transit absorption signature in the Lyman  $\alpha$  line wings (the nominal 1.5% obscuration by the planetary disk is below the data S/N), VM003 calculated a *relative* absorption depth using wings of the Lyman  $\alpha$  line as flux reference. This method aims at correcting for any intrinsic

\*Because the escape of hydrogen atoms is strengthened in this paper, we renew our proposal to use the nickname “Osiris” for the planet HD 209458b who loses mass like the Egyptian god.

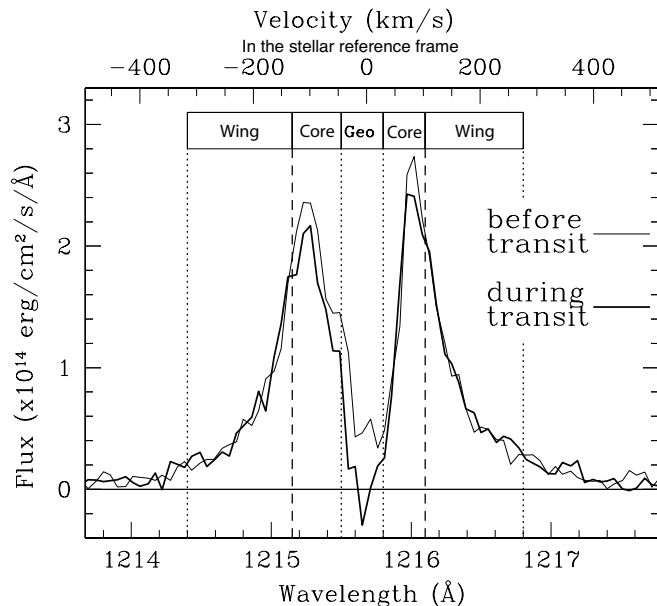


FIG. 1.— The observed HD 209458 Lyman  $\alpha$  profiles as observed by Vidal-Madjar et al. (2003) before and during the planetary transit. The BJ007 re-analysis of nearly the same data set produced a similar Lyman  $\alpha$  line profile. The two vertical dashed lines define the limits  $\lambda_1$  and  $\lambda_2$  of the line core where HI planetary absorption takes place. In VM003 as well as in BJ007, the central part of the line (noted “Geo”) possibly perturbed by the Earth geocoronal emission is omitted from the analysis. The line wings are used by VM003 as a flux reference to correct for the stellar Lyman  $\alpha$  intrinsic variations.

sic and unknown changes in the Lyman  $\alpha$  stellar flux (see § 4). As illustrated in Fig. 1, VM003 defined two spectral domains : the line core from  $\lambda_1$  to  $\lambda_2$  (called “In” in VM003 and “Core” in Fig. 1; excluding the part of the spectrum contaminated by the geocoronal Lyman  $\alpha$  emission), and the remaining wavelength domain in the wings of the line used as a flux reference from 1214.4Å to  $\lambda_1$  and from  $\lambda_2$  to 1216.8Å (called “Out” in VM003 and “Wing” in Fig. 1). The best domain defined by  $\lambda_1$  and  $\lambda_2$  is found by varying the positions of these two wavelengths until the strongest absorption signal is identified. VM003 found that the strongest absorption relative to the line wings takes place in the line core between  $\lambda_1=1215.15$  and  $\lambda_2=1216.10$ Å (excluding the central geocoronal region).

Because the HI absorption takes place only in the central part of the Lyman  $\alpha$  line, the absorption depth measurement must decrease for increasing wavelength range, including wings of the line where there is no absorption. This has already been found by VM004 with an independent data set obtained with STIS in the G140L low resolution mode. In the low resolution data, the Lyman  $\alpha$  stellar emission line is not spectrally resolved and only the total Lyman  $\alpha$  flux can be evaluated. VM004 obtained a  $(5 \pm 2)\%$  transit absorption depth over the whole line, in agreement with the estimate obtained from the VM003 dataset (Table 1).

To compare the VM003 result to that of BJ007, we can also calculate the transit absorption depth over the spectral domain as defined by BJ007 using the spectra of VM003. Keeping the same approach as in VM003 to account for stellar Lyman  $\alpha$  variations, we evaluate the planetary absorption during transit using the line wings as flux reference. We find a mid-transit absorp-

tion of  $(7.3 \pm 2.0)\%$  over the same spectral region used by BJ007, which is in agreement with the BJ007 result of 8.9% considering that the data set is the same, except for the addition of two HST orbits to the nine used by VM003. This result shows that, considering the same wavelength range, similar transit absorption depths are found in the VM003 and BJ007 spectra (Table 1).

The uncertainty and noise appear to be lower in BJ007 than in VM003. The difference is explained by the larger wavelength range used by BJ007 to estimate the Lyman  $\alpha$  flux and by the uncertainty introduced by the correction of the Lyman  $\alpha$  variations applied by VM003 (see § 4).

In short, the results given in VM003 and BJ007 for Lyman  $\alpha$  absorption depths can be reconciled. The apparent difference is basically due to the width of the spectral domain over which the absorption is computed, acknowledging that the HI absorption does not cover the whole extent of the stellar Lyman  $\alpha$  line. When using a larger wavelength domain, the absorption signal is diluted and the absorption depth measurement is lower, as found in BJ007 compared to VM003, and in VM004 compared to BJ007.

### 3. HIGH VELOCITY BLUE-SHIFTED ABSORPTIONS

Another argument, made by BJ007 against the evaporation scenario, is that the blue-shifted absorption (produced by hydrogen atoms at speeds up to  $-130$ km/s identified by VM003) is not confirmed in the BJ007 analysis. Velocities of  $-130$ km/s are above the escape velocity of about  $\sim 42$  km/s (at  $1 R_p$ ). If observed, high velocity atoms must be escaping the planet.

Following the same approach as above using the VM003 dataset, we evaluate the absorption seen during transit within the “blue” and the “red” sides of the wavelength domain defined by BJ007. In this domain, we find  $(9.8 \pm 1.8)\%$  and  $(5.2 \pm 1.0)\%$  absorption in the “blue” and the “red” sides, respectively. Therefore, the large spectral domain defined by BJ007 (including velocities up to  $\pm 200$  km/s) shows a significant absorption in both blue and red sides with, as found in VM003, an absorption stronger in the blue than in the red.

Finally, although very little work has been published to explain these high velocities, they can be produced by radiation pressure from the intense Lyman- $\alpha$  flux of the nearby star (see the velocity diagram and the cometary shape of the escaping atoms in Fig. 3 of Vidal-Madjar & Lecavelier des Etangs (2004)). In which case, a difference between blue and red absorptions is expected.

### 4. THE LYMAN- $\alpha$ STELLAR VARIATIONS

In previous works, corrections for stellar variations was done either using the wings of the line (VM003) or the observations before and after the transit (VM004), while BJ007 correction was done by averaging the flux variations by fitting a standard transit curve over the phase-folded data points (see Fig. 2 in BJ007).

Contrary to the claim made by BJ007, the Lyman  $\alpha$  variations of HD 209458 are not necessarily relatively large but normal for a quiet solar type star (Vidal-Madjar, 1975). In fact, when data are phase-folded, the apparent variations can be artificially enhanced due to the superimposition of observations made at different dates. Moreover, real stellar fluctuations are combined

TABLE 1  
EVALUATED LYMAN  $\alpha$  ABSORPTION OVER VARIOUS SPECTRAL DOMAINS

Spectral domain	Line core 1215.15-1216.10Å VM003 limits	Intermediate 1214.83-1216.43Å BJ007 limits	Whole line 1210-1220Å
Published absorption (%) (reference and data set)	$15 \pm 4$ (VM003)	$8.9 \pm 2.1$ (BJ007)	$5 \pm 2$ (VM004)
Absorptions using VM003 dataset <sup>a</sup>	$15.1\% \pm 4\%$	$7.3\% \pm 2.0\%$	$5.7\% \pm 1.9\%$

<sup>a</sup> Absorption evaluated using VM003 dataset and following the VM003 method with wings as flux reference.

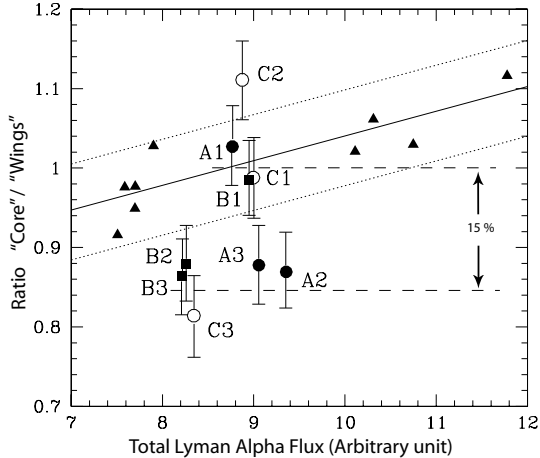


FIG. 2.— Plot of the Solar and HD 209458 “Core”/“Wing” ratios as a function of the total Lyman  $\alpha$  flux (“Core”+“Wing”). “Core” and “Wing” domains are defined in Fig. 1. Triangles are for Solar values. Circle and square symbols are for HD 209458 and correspond to the three HST visits A, B, and C, each visit including three successive HST orbits, namely 1, 2 and 3 (see VM003 for details). The linear regression to the Solar values is shown along with the upper and lower limits (dotted lines). The HD 209458 values show basically two groups. In a first group, out-of-transit measurements A1, B1 and C1 are within the limits of the Solar fluctuations. The second group consists of in-transit measurements (where A2, B2, B3 and C3 are the closest mid-transit) that are well below the Solar fluctuations. The comparison between the dispersion within a group and the amplitude of the transit signature between the two groups, the absence of correlation between the HD 209458b “Core”/“Wing” ratios and the total Lyman  $\alpha$  flux, both invalidate the suggestion that HD 209458 Lyman  $\alpha$  activity corrupts the transit signature.

with significant noise which is expected to be large because of the limited number of photons in the short temporal bins.

The Sun can be used as a proxy to study the possible variations of the flux and shape of the HD 209458 Lyman  $\alpha$  line. HD 209458 is a Solar type star (G0V) whose similarity with the Sun is demonstrated by the observation of the chromospheric CaII line profiles, which are relatively quiet for both stars. From observations obtained with SOHO (Solar and Helio-centric Observatory, Lemaire et al., 2002), we show that the core-to-wing ratio of the Solar Lyman  $\alpha$  line varies by about  $\pm 8\%$ , while it varies by about  $\pm 6\%$  for a given total Lyman  $\alpha$  flux (Fig. 2). HD 209458 is expected to have the same behavior and the 15% transit measurements is unlikely to be due to stellar variations. This is strengthened by the HD 209458 Lyman  $\alpha$  measurements which present two different groups of core-to-wing flux ratios (Fig. 2) : the

ratios measured before the transit and the ratios during the planetary transit. Although these measurements are obtained at various epochs, the dispersion within a given group is small and within the error bars, while the difference between the measurements taken during the transit compared to the reference measurements taken before the transit is significant and larger than variations observed in the Sun. This behavior is unlikely to be coincidental and corresponds to the expected signal for a cloud of HI atoms in the environment of HD 209458b.

Moreover, the dispersion of these individual measurements shows no correlation with the total Lyman  $\alpha$  flux. This shows that the stellar variations are unlikely to be responsible for the observed Lyman  $\alpha$  core-to-wings variations. The core-to wing variations are thus more likely related to the planetary transit.

Finally, it is extremely unlikely that stellar variations can mimic a transit light curve as seen in Fig. 2 of BJ007, when measurements are phase-folded with the planetary orbital ephemerides.

In summary, the stellar variations are taken into account by VM003 by comparing the variations in the core to the variations in the wings of the line, and by BJ007 by averaging a smooth transit light curve over a fluctuating Lyman  $\alpha$  stellar flux. The similarity of the resulting absorption depths, using the BJ007 and VM003 dataset, when evaluated over the same spectral domain (Table 1) shows that the Lyman  $\alpha$  stellar variability does not corrupt the transit evaluation whatever the approach used for the data analysis.

## 5. THE SIZE OF THE ABSORBING CLOUD AND THE ROCHE LOBE

BJ007 compares the 8.9% absorption depth derived in his work to the absorption caused by an occulting disk with a size of  $\sim 4.08 R_P$  supposed to be the size of the Roche lobe as calculated using equations found in Gu et al. (2003). In the case of HD 209458b, a disk with a radius of  $\sim 4.08 R_P$  corresponds to an absorption depth of about 25% during transit. BJ007 thus concludes that the observed hydrogen atoms are inside the Roche lobe and cannot escape the planet.

First, as discussed above, the BJ007 evaluation of  $\sim 9\%$  is only a fraction of the full HI absorption depth in the line core. Second, the formula of Gu et al. (2003) for computing the Roche lobe corresponds to the Lagrangian point L1 between the star and the planet, i.e. the most distant Roche limit position relative to the planet (see Eq. B.8 and discussion in Lecavelier des Etangs, 2007).

However, the Roche lobe around the planet is not spherical but elongated toward the star (see e.g. Lecavelier des Etangs et al. 2004). In a transit configuration, the observed limit of the Roche lobe is in a direction perpendicular to the star-planet direction. In this perpendicular direction, the Roche lobe extension is about 2/3 of the extension toward the L1 point. Therefore, it is more appropriate to use an average distance to the Roche lobe, which was given by VM003 to be  $\sim 2.7 R_P$  (Paczynski, 1971). A filled Roche lobe corresponds to about 12% absorption. This value is comparable to the HI observation of  $\gtrsim 10\%$  absorption depth in the line core. We can conclude that HI atoms reach the Roche lobe or beyond, in agreement with the models of atmospheric escape.

In addition, although observation of hydrogen atoms outside the Roche lobe is a direct evidence for escape, it is not a necessary condition. Even filling-up half a Roche lobe would imply escape rates large enough to significantly affect atmospheric structure (Lecavelier des Etangs et al. 2004). Thus, whether the hydrogen cloud actually fills up the Roche lobe or not, the large extension of the upper atmosphere (and possibly a cometary shape due to radiation pressure) shows that the atmosphere is indeed escaping.

#### 6. CONSEQUENCE: EVAPORATION IS CONFIRMED

We have demonstrated that the BJ007 analysis is in agreement with HI escape from the HD 209458b atmosphere. Even if one considers that the absorption value given by BJ007 is correct, then either: i) this  $\sim 9\%$  absorption depth is taking place over the whole spectral range of  $\pm 200$  km/s, or ii) the  $\sim 9\%$  absorption is the result of an unresolved larger absorption within a narrower wavelength range, produced by atoms below the escape velocity of about 42 km/s. In the first case, HI atoms are detected to move at velocities much larger than the escape velocity. In the second case, the absorption takes place over a narrow spectral range,  $\sim 5$  times narrower than the range considered in BJ007. In this narrow wavelength range, the absorption must be  $\gg 12\%$  and HI atoms must be present beyond the Roche lobe. In both alternatives, the result of the data analysis described in BJ007 shows that HI must be escaping the planet atmosphere.

#### 7. CONCLUSION

BJ007 called into question the VM003 discovery of the atmospheric escape from the HD 209458b extrasolar

planet. BJ007 gives two main arguments : i) the absorption depth is smaller than previously estimated and the Roche limit is not reached, and ii) the data analysis is corrupted by intrinsic stellar Lyman  $\alpha$  variations. The first argument is not correct because the absorption is not taking place over the whole Lyman  $\alpha$  line. The absorption depth measurements depend on the considered wavelength range. In addition, the Roche lobe shape and orientation must be taken into account when comparing the size corresponding to these absorption depths with the size of the Roche lobe. The second objection is rejected by recalling that VM003 corrected for the stellar variations using the overall stability of the line shape and the line wings as flux reference.

Finally, despite the affirmation in the introduction of BJ007, works to transpose these observations into estimates of escape rate have been made early in VM003 and recently in Schneider et al. (2007). As stated by our anonymous referee, these “observational” estimates agree with the most recent and sophisticated models which all find rather good agreement with mass loss rates of  $\sim 3 - 7 \times 10^{10} \text{ g s}^{-1}$ . Therefore, at the orbital distance of HD 209458b, atmospheric escape does not strongly affect the evolution of the planets, in accord with the evolutionary studies.

Last, but not least, Ben Jaffel (2007) performed an independent, thorough and careful analysis of the best available data set for measuring the Lyman  $\alpha$  transit absorption depth. Despite a misinterpretation of the resulting spectra, this work confirms that the signal detected in VM003 is indeed present and is not related to the data reduction process. Therefore, in the atmosphere of HD 209458b, HI appears to be the only species to have been detected with two independent datasets, and now with independent data analyses. The BJ007 data analysis strengthens the detection of the extended escaping atmosphere of HD 209458b, in agreement with numerous theoretical studies of this phenomenon (e.g., Lammer et al. 2003; Lecavelier des Etangs et al. 2004; Yelle 2004, 2006; Baraffe et al. 2005; Tian et al. 2005; Garcia-Munoz 2006).

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